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ABSTRACT

Snow Water Equivalent (SWE) is one of the most important parameters for accurate snowmelt runoff prediction. Conventionally, SWE is monitored using observations made at widely scattered points in or around specific watersheds. Remote sensors, which provide data with better spatial and temporal coverage, can be used to improve the SWE estimates. Microwave radiation, which can penetrate through a snowpack, may be used to infer the SWE.

Calculations made from a microscopic scattering model are used to simulate the effect of varying SWE on the microwave brightness temperature. Data obtained from truck mounted, air-borne and space-borne systems from various test sites have been studied. The simulated SWE compares favorable with the measured SWE. In addition, whether the underlying soil is frozen or thawed can be discriminated successfully on the basis of the polarization of the microwave radiation.

CONTENTS

	Page
ABSTRACT	iii
I. INTRODUCTION	1
II. THEORY	2
III. COMPARISONS	4
IV. CONCLUSIONS	8
REFERENCES	9

TABLES

Table		Page
1	Comparison of Truck Mounted Experimental Data	11
2	Comparison of Aircraft Experimental Data	12

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SNOW WATER EQUIVALENT DETERMINATION
BY MICROWAVE RADIOMETRY

I. INTRODUCTION

Snow accumulation and depletion is a highly critical parameter in the western United States. Meltwater from mountain snowpacks provides much needed water for hydropower generation and irrigation. As much as 70 percent of the water supply for the western United States is directly derived from the spring runoff of the snowpack. Knowledge of the available water volume in advance of the runnoff period will permit better management of the expected runoff in the spring. The spring meltwater also provides recharge to the upper soil mantle for spring wheat and other grains in agricultural regions. Information on the water equivalent of these non-mountainous snowpacks could indicate areas of potential moisture deficiencies or surplus.

In order to monitor the snow water equivalent accurately for these hydrological applications, measurements of snow covered area, snow depth, density and liquid water content are essential. In addition to these snow properties, the condition of the underlying soil is important for estimating the amount of snowmelt water that will be retained in the soil mantle. Conventionally, these observations are collected manually by snow surveyors using skis or snowmobiles, and automatically from a few unattended, isolated stations which are instrumented with pressure pillows and other in-situ sensors. These data collection methods are time consuming and measurements are taken at only a limited number of points along selected snow survey courses. Consequently, the snow water equivalent estimates may differ significantly from the actual water equivalent of a snowpack because of the sparsity of the observations made in space and time. The use of remote sensing techniques may offer a way to augment or complement the conventional observations by providing high spatial density and repetitive observations over entire watersheds.

Sensors on board present operational satellites scan the earth in the visible, near infrared and thermal infrared portions of the electromagnetic spectrum. Snow covered area estimates from

primarily visible images for several test watersheds have been found to be well correlated with the actual snowmelt runoff (Rango and Peterson, 1980). However none of these short wavelength sensors can provide the information on the depth and water equivalent of the snowpack that could further improve water resources management. Microwaves have the capability of penetrating the snowpack, thus that portion of the electromagnetic spectrum has considerable potential for monitoring snowpack water equivalent and wetness (Rango, et al., 1979). In addition, microwave radiation of about 3 cm wavelength or longer may penetrate through a typical snowpack (~ 1 m depth) to provide information on soil conditions (frozen or thawed) beneath the snowpack. These conditions greatly influence the prediction of snowmelt runoff yields.

In order to quantitatively determine the water equivalent of the snowpack by microwave radiometry, it is necessary to understand the behavior of microwave radiation within the snowpack. This paper describes a model of the microwave emission characteristics of snowpacks for various snow conditions. Microwave radiometric data measured by truck-mounted, airborne and space-borne sensor systems have been compared with the calculated results of a microscopic scattering model (Chang, et al., 1976). The snow depth and water equivalent estimates derived from the model calculations compare favorably with the limited ground truth information.

II. THEORY

The intensity of microwave radiation emitted from a snowpack depends on the physical temperature, grain size, density and the underlying surface conditions of the snowpack. By knowing these parameters, the radiation emerging from a snowpack can be derived by solving the radiative transfer equation. The radiative transfer equation for an axially symmetric inhomogeneous medium can be written in the form of an integro-differential equation

$$\mu \frac{dI(x,\mu)}{dx} = -\sigma(x)\, I(x,\mu) + \sigma(x) \left\{ [1-\omega(x)]\, B(x) + \tfrac{1}{2}\omega(x) \int_{-1}^{1} P(x,\mu,\mu')\, I(x,\mu')\, d\mu' \right\}, \qquad (1)$$

where the radiation intensity $I(x, \mu)$ is at depth x traveling in the direction making an angle whose cosine is μ with the normal toward the direction of increasing x (Figure 1). The functions $\sigma(x)$,

$\omega(x)$, $B(x)$ and $P(x, \mu, \mu')$ are prescribed functions of their arguments. They are referred to as the extinction per unit length, the single scattering albedo, the source and the phase functions, respectively. The snow grains scatter the electromagnetic radiation incoherently and are assumed to be spherical in shape and randomly spaced within the snowpack. Further discussions of the microscopic model can be found in Chang et al., (1976). Equation (1) is solved numerically by the invariant imbedding technique (Chang and Choudhury, 1978). This technique is based on the principle that the radiation emerging from a semi-infinite, plane parallel medium is invariant with respect to addition (or subtraction) of layers of arbitrary thickness to (or from) the medium. Expressed numerically, this technique solves the radiative transfer equation via recurrence relations.

By this method, the emerging brightness temperatures are calculated for snowpacks with different parameters. The snow depth varies from 10 cm to 250 cm while the water equivalent varies from 3 cm to 100 cm. The mean snowpack grain size varies from .25 mm to .5 mm in radius. Two different types of underlying surface conditions are considered. They are (1) frozen soil and (2) unfrozen soil with 20% moisture content. Figures 2 and 3 show the calculated brightness temperature as a function of snow water equivalent (SWE) for 37 GHz radiation with a look angle of 50 degrees. In this paper we address only the dry snow condition; the wet snow condition will be addressed in a subsequent paper.

Based on these calculations we may conclude that the brightness temperature at 37 GHz tends to decrease rapidly with increasing SWE. Also, the calculated rate of change of brightness depends strongly on the grain size, yet it is almost independent of the snow density. This characteristic may be used as the basis to determine the SWE. However, the emerging 37 GHz brightness from a snowpack depends on the underlying soil conditions. In order to resolve this ambiguity, measurements from another frequency preferably longer wavelength are required. The measurements at 10.7 GHz provide sufficient information needed for this purpose.

Water is a polar molecule and it has a very large dielectric constant at microwave frequencies. This results in a large reflectivity difference from a frozen and an unfrozen soil surface. For incidence angles not equal to zero, the polarization factor

$$P = \frac{T_V - T_H}{T_V + T_H} \tag{2}$$

is commonly used to reflect the different surface conditions. The calculated polarization factor for 10.7 GHz ranges from 0.08 to 0.1?5 for unfrozen soil with 20% soil moisture and from 0.0?2 to 0.051 for frozen soil. Thus by a simple discriminant analysis, these two categories can be separated by using the polarization factor:

$$P > 0.07 \quad \text{unfrozen soil} \tag{3}$$

$$P < 0.07 \quad \text{frozen soil} \tag{4}$$

III. COMPARISONS

There have been several different experiments designed to measure the microwave brightness temperature as a function of snow depth or water equivalent. The first truck-mounted radiometer experiment was conducted on a site in the northern part of the Sierra Nevada Range near Truckee, CA by Edgerton, et al., 1973. They reported a smooth and pronounced reduction of 37 GHz brightness temperature during the snow accumulation period. These results indicate that microwave brightness temperatures may be used to measure the water equivalent of a snowpack. Recently, several groups have been involved in microwave snowpack characterization experiments using ground-based systems (Stiles and Ulaby, 1980, Hofer and Matzler, 1980, and Chang, et al., 1979).

The results reported by various investigators are consistent. Due to different snow conditions in different geographical locations, however, some dissimilarities have also been reported. Typical brightness temperatures at 37 GHz and the related snow information from different experiments are tabulated in Table 1. For comparison purposes, the predicted SWE is obtained by converting the measured brightness using the curves in Figures 2 and 3. Due to the lack

of adequate measurements of the mean snow crystal radius in each experiment, only one mean radius value (0.35 mm) was assumed for this initial simulation of the SWE in all test sites.

From Table 1 it is quite encouraging that the predicted SWE values are comparable with the measured results for all the snowpacks, except in the deep SWE in Switzerland. Generally predictions are successful for snowpacks shallower than one meter. At Frazer, CO the percent polarization factor ranges from 0.02 to 0.04. These values correspond to the frozen soil condition as observed at this particular valley site.

Snow crystal size usually increases as measurements are made deeper in the snowpack (Gow, 1969). The radius for new dry powder snow on top of a snowpack normally ranges from 0.05 to 0.1 mm. Whereas depth hoar, located at the bottom of a snowpack, may have a radius from 1 mm to several mm. Since at present, the mean crystal size is assumed to be a fixed value (0.35 mm) in this study, it is possible to adjust the mean snow crystal radius as a parameter to obtain a better fit of the present data. For example, if we choose the radius to be 0.3 mm, then the brightness temperature observed at Fraser indicates a SWE of 25 cm instead of 16 cm as obtained using 0.35 mm for mean radius. Therefore, in order to obtain reliable estimates of SWE by this technique, it is necessary to carefully characterize the physical size of the crystals within the snowpack.

Use of the 37 GHz brightness to predict the SWE is limited, because the 37 GHz radiation can only penetrate the top 50 to 100 cm of the snowpack (Stiles and Ulaby, 1980, and Hofer and Matzler, 1979). Thus in case of a snowpack several meters in depth, the mean crystal radius should only be calculated by using the crystal size from the uppermost portion that the microwaves sample. This top layer probably has a much smaller mean radius than the entire snowpack. Recent measurements by Matzler et al. (1980) in Switzerland showed that the mean radius of the 1979 snowcover is about 0.25 mm. If this value is taken as the crystal radius, then the SWE predicted using Figure 2 closely approximates to the measured SWE of 50 cm.

During the winters of 1976, 1977 and 1980 several aircraft missions took place in the Colorado Rockies for snowpack studies. Steamboat Springs, Rabbit Ears Pass and Walden, CO were the major study sites. The radiometers on board the aircraft include a four channel Multi-Frequency Microwave Radiometer (MFMR) and a Passive Microwave Imaging System (PMIS). Coordinated with these flights, extensive ground truth information was gathered. Snow density, water equivalent, depth, wetness, approximate grain size, layer classification and soil condition were measured by the ground truth teams (Jones, 1976, 1977, 1979, 1980a and 1980b). For the purpose of this study the data were averaged over the entire flight line for better comparison with the large microwave radiometer footprint obtained from airborne sensors. The 37 GHz brightness is used to predict the SWE while the 10.7 GHz brightness is used to determine the underlying soil conditions. Table 2 shows the results of measured SWE as compared with SWE derived from microwave brightness. The comparison between the predicted and measured SWE is good everywhere except at Rabbit Ears Pass. Again, the discrepancy probably is due to the arbitrary choice of 0.35 mm for the assumed grain size used in the model. At Rabbit Ears Pass the snow was about 1.5 m in depth. Even with such deep snow, the percent polarization factor derived from the 10.7 GHz measurement does reflect the underlying soil conditions when using 0.07 as the divider between the unfrozen and frozen soil.

Microwave measurements from spaceborne systems have been available since the launch of the Nimbus-5 satellite in December, 1972. Rango, et al. (1979) and Foster, et al. (1980) used the Nimbus 5 and 6 Electrically Scanned Microwave Radiometer (ESMR) data in an attempt to determine if a correlation existed between snow depth and brightness temperature in relatively homogeneous regions of the United States, Canada and Russia. Statistically significant regression relationships and reasonably high coefficients of determination ($R^2 \sim 0.8$) were obtained in these studies. These results demonstrate a potential for estimating snow depth by passive microwave data from spaceborne sensors.

In this study we will report some preliminary results derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR). SMMR is a five frequency, dual polarized microwave radiometer which measures the upwelling microwave radiation at 6.6, 10.7, 18.0, 21.0, and 37.0 GHz while scanning 25° to either side of the spacecraft with a constant incidence angle of approximately 50° with respect to the Earth's surface. The spatial resolution varies from 25 km for the 37 GHz to 150 km for the 6.6 GHz. Detailed descriptions of this instrument can be found in the Nimbus-7 User's Guide (Gloersen and Hardis, 1978).

The study areas chosen were (1) central Russia and (2) the high plains of Canada (Foster et al., 1980). The vegetation, topography, climate and latitude of these two areas are similar. The generally flat terrains of these areas, which is sometimes broken by hills is covered with various grasses. Both of these two areas experience very cold winters with snow possibly covering the ground from December to March.

Due to limited available snow course data, it is rather difficult to compile SWE data in a timely fashion for comparison with the satellite measurements. In this study SWE is calculated by multiplying the snow depth and the snow density. Snow depth information was obtained from meteorological stations, whereas the snow density was assumed to be 0.3 g/cm^3 for all the calculations (variations from this assumed density could account for some of the scatter observed in the data). Figure 4 shows the 37 GHz vertical polarization brightness temperature versus the snow depth for the Canadian and Russian test sites as compared with the calculated results. The figure shows that most of the data points fall in the range of mean radius of 0.3 to 0.5 mm. These results provide us more confidence in the assumed mean radius (0.35 mm) used in this study. The time period of the SMMR data used is February 15 to 21, 1979. During this time period the snow depth variation across the study areas is quite limited (from 1 to 30 cm). Although the foot-print of each brightness measurement represents a rather large area (25 km X 25 km), the effect of snow cover can still be observed. Figure 5 shows the scattering of SMMR 37 GHz brightness temperature versus snow depth for the Russian test site. The linear regression technique gives a R^2 of 0.75 for the T_B and

snow depth. The data display considerable scatter, which is probably due to the inhomogeneity within each footprint and the assumptions used in this study. The theoretically calculated brightness curve fits well with observations and can be utilized to infer the snow depth or SWE from microwave brightness temperature measured by spaceborne sensors. No attempt has been made in this study to relate the polarization factor to the freeze/thaw soil condition determination, because there is no reliable "ground truth information" for comparison.

IV. CONCLUSIONS

The microwave radiometer observations can be utilized to infer the snow water equivalent under dry snow conditions. The results from a scattering model match well with the experimental results. The capability of the 37 GHz radiometer has been demonstrated by using data collected by ground experiments, aircraft and spacecraft measurements. For deeper snowpacks, a wavelength longer than 0.8 cm is required to infer the snowpack information. The polarization factor derived from the 10.7 GHz brightness temperature provides an adequate index of the underlying soil condition.

Due to the strong dependence of the emerging brightness temperature on the mean crystal radius, it is necessary to carefully characterize the crystal sizes within the snowpack. In addition, crystal size distribution should be monitored and documented in order to account for the different type of snow metamorphism found in different snow sites.

At present, the poor sensor resolution from satellite observations limits the use of the satellite to large homogeneous regions such as the high plains. Even this coarsely derived information could be valuable for runoff prediction purposes for the time period right before the rapid spring melt in these test sites. In these areas, snow also provides the necessary insulation for the underlying vegetation such as winter wheat. Satellite derived information on snow depth could be the key to early detection of winter kill. This information will greatly enhance the accuracy of overall crop yield prediction. As satellite spatial resolution improves with future generations of microwave radiometers, applications should be found in other areas such as intermountain valleys and large mountain plateaus. Then the capabilities of microwave radiometry will become more directly applicable to seasonal and short term runoff forecasting.

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Table 1. Comparison of Truck Mounted Experimental Data

Test Site	T_B	Incidence Angle	Polarization	Snow Water Equivalent	
				Measured	Predicted
Truckee, CA	233K	45°	V	10 cm	9 cm
(Edgerton, et al., 1973)	210K	45°	V	20 cm	16 cm
Steamboat Spring, CO	205K	57°	H	10 cm	9 cm
(Stiles and Ulaby, 1980)	188K	57°	H	20 cm	15 cm
Fraser, CO (Chang, et al., 1979)	210K	50°	V	21 cm	16 cm
Davos, Switzerland (Hofer and Matzler, 1980)	210K	53°	V	50 cm	16 cm

Table 2. Comparison of Aircraft Experimental Data

Test Site	$T_{B(37H)}$	$T_{B10.7}$	Polarization Factor	Snow Water Equivalent		Ground Cover
				Measured	Predicted	
Steamboat Springs, CO March 1976	165	245 V 199 H	0.10	16.1 ± 7cm	17 cm	Wet
Walden, CO March 1976	235	268 V 258 H	0.02	2.8 ± 1.5 cm	3 cm	Frozen
Steamboat Springs, CO March 1977	200			10.4 ± 3.7 cm	11 cm	Frozen
Walden, CO March 1977	254			0.12 cm	0 cm	Frozen
Steamboat Springs, CO December 1979	240			6.6 ± 0.6 cm	2 cm	Frozen
Rabbit Ears Pass, CO February 1980	234	263 V 245 H	0.04	49.3 ± 13 cm	4 cm	Frozen
Steamboat Springs, CO February 1980	197			19.8 ± 2 cm	12 cm	Frozen
Steamboat Springs, CO March 1980	162	255 V 210 H	0.10	30.9 ± 5.6 cm	29 cm	Wet
Walden, CO March 1980	194			9.9 ± 4.8 cm	12 cm	Wet

FIGURE CAPTIONS

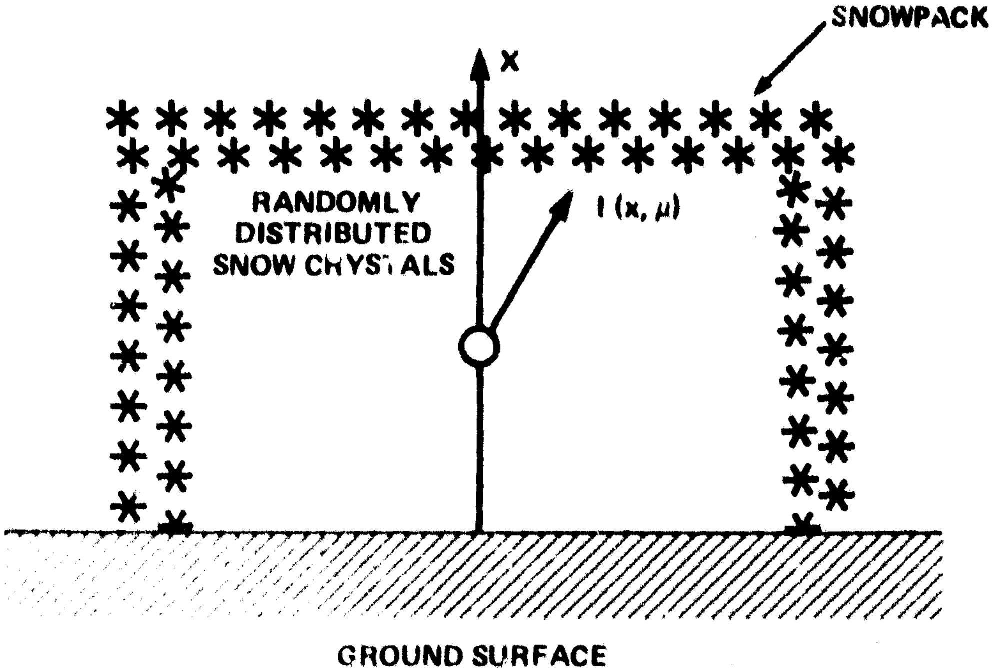
Figure 1. Radiation Intensity of $I(x, \mu)$.

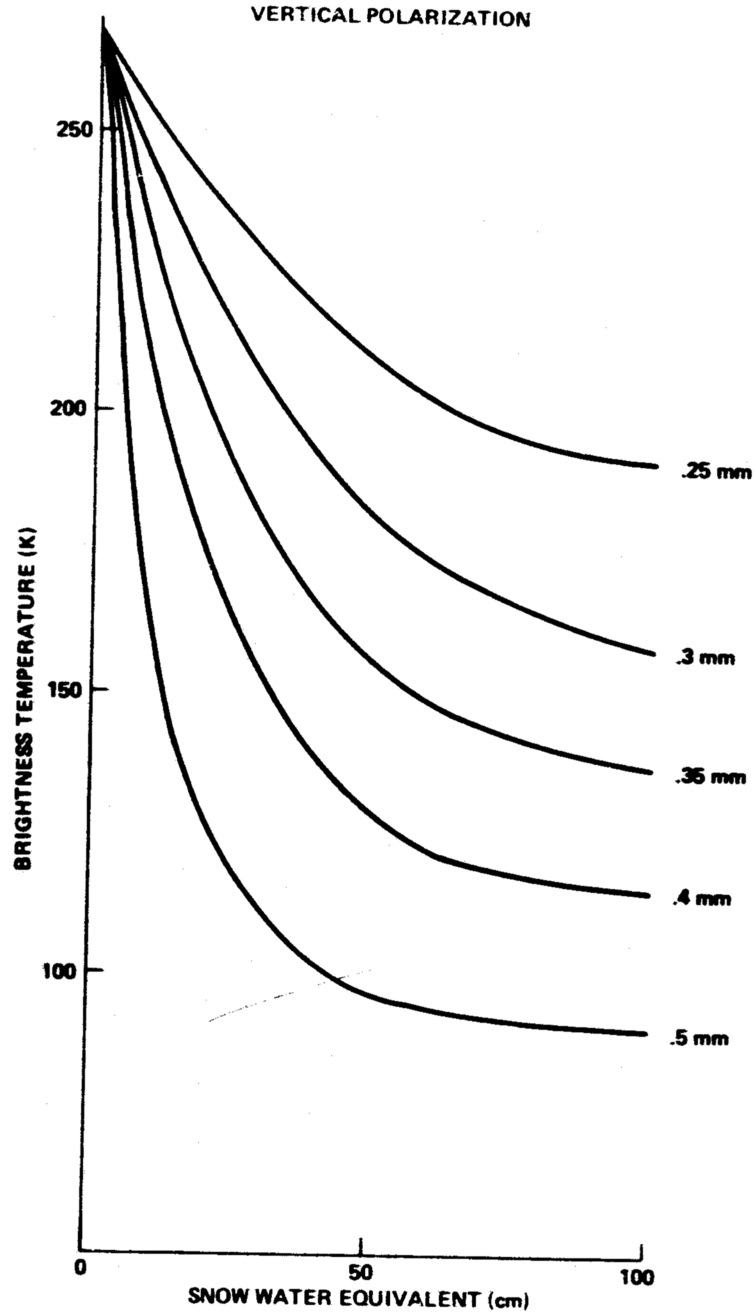
Figure 2. Calculated 37 GHz Brightness Temperature vs. Snow Water Equivalent Over Frozen Ground (Incidence Angle = 50°).

Figure 3. Calculated 37 GHz Brightness Temperature vs. Snow Water Equivalent Over Unfrozen Soil (Incidence Angle = 50°).

Figure 4. Comparisons of Calculated Brightness vs. Measured Brightness for Different Snow Depths (37 GHz Vertical Polarization, $\theta = 50°$).

Figure 5. NIMBUS-7 SMMR 37 GHz Vertically Polarized Microwave Brightness Temperature (T_B) vs. Snow Depth (Russia) $R^2 = 0.75$.


SNOWPACK
X
RANDOMLY
DISTRIBUTED
SNOW CRYSTALS
I (x, μ)
GROUND SURFACE


VERTICAL POLARIZATION
BRIGHTNESS TEMPERATURE (K)
250
200
150
100
0
50
100
SNOW WATER EQUIVALENT (cm)
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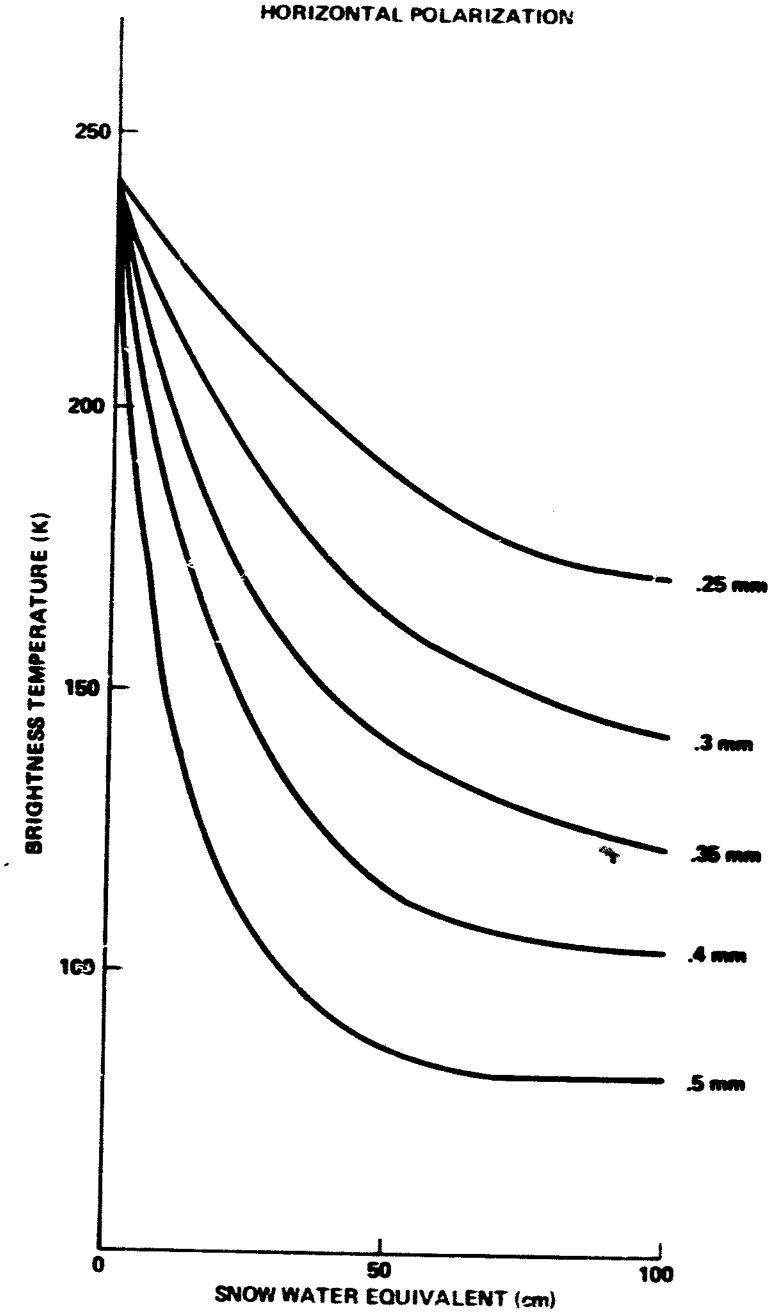
.3 mm
.35 mm
.4 mm
.5 mm


HORIZONTAL POLARIZATION
BRIGHTNESS TEMPERATURE (K)
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200
150
100
0
50
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SNOW WATER EQUIVALENT (cm)
.25 mm
.3 mm
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.4 mm
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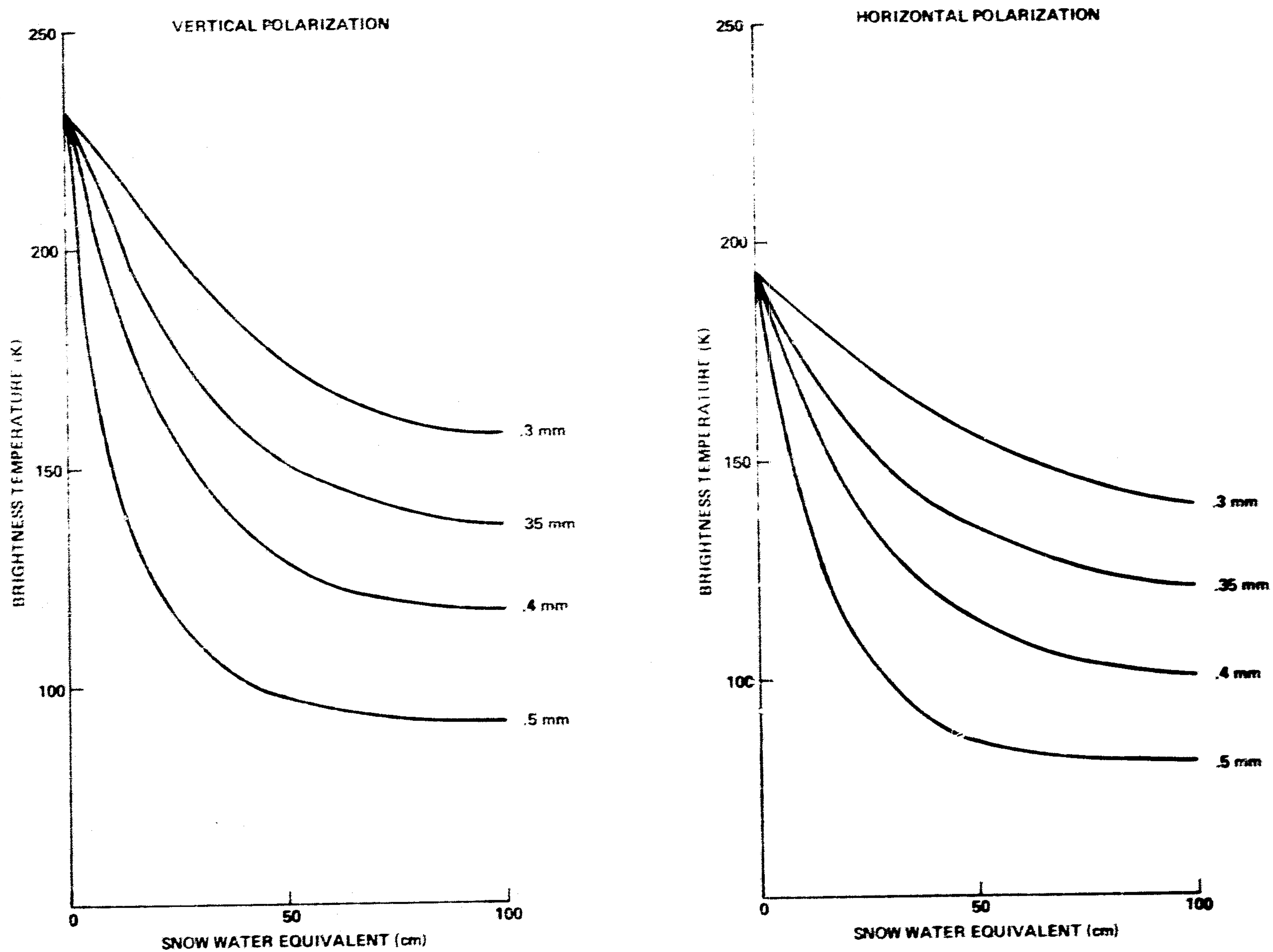
VERTICAL POLARIZATION
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SNOW WATER EQUIVALENT (cm)
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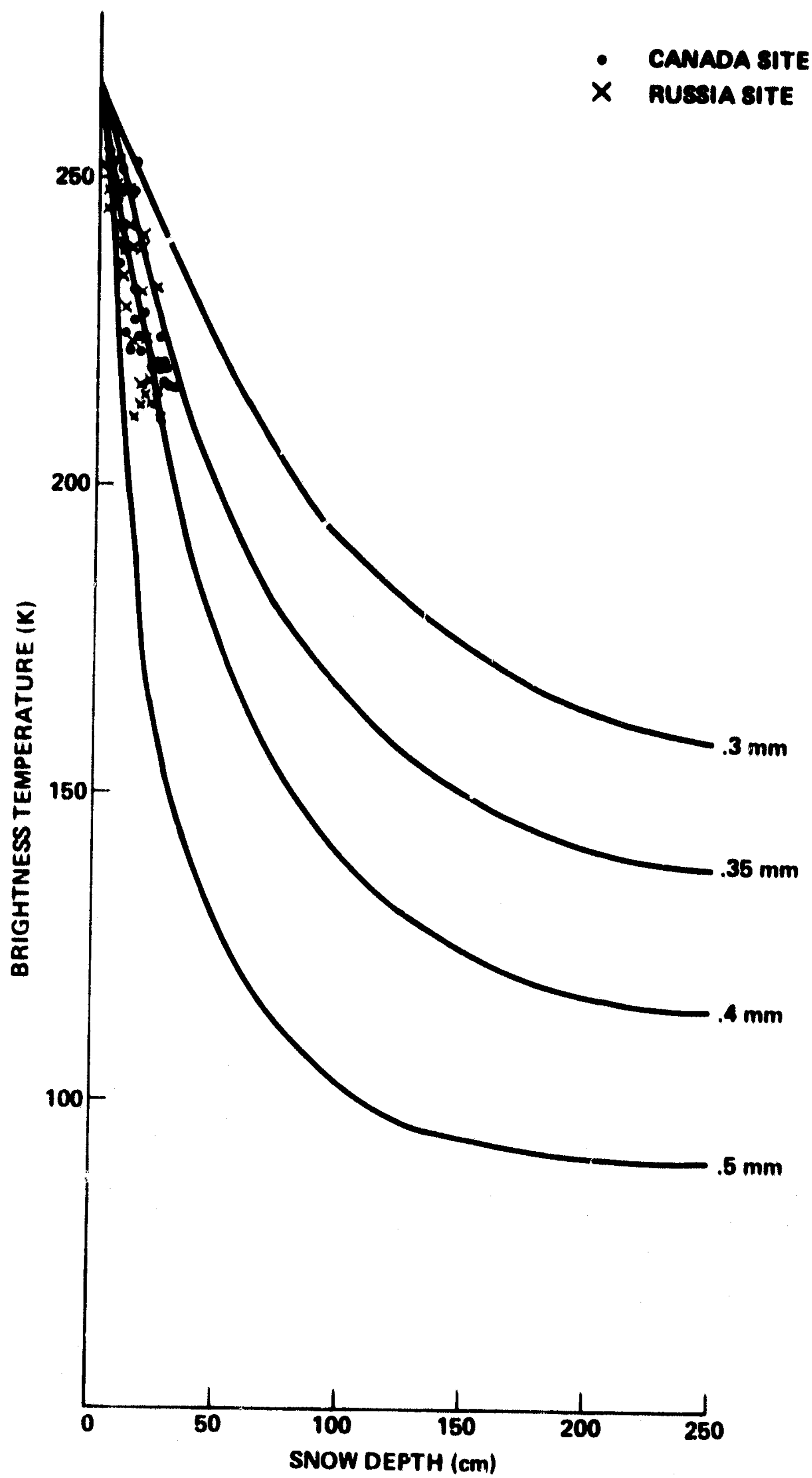
SNOW WATER EQUIVALENT (cm)


CANADA SITE
RUSSIA SITE
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200
150
100
BRIGHTNESS TEMPERATURE (K)
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.35 mm
.4 mm
.5 mm
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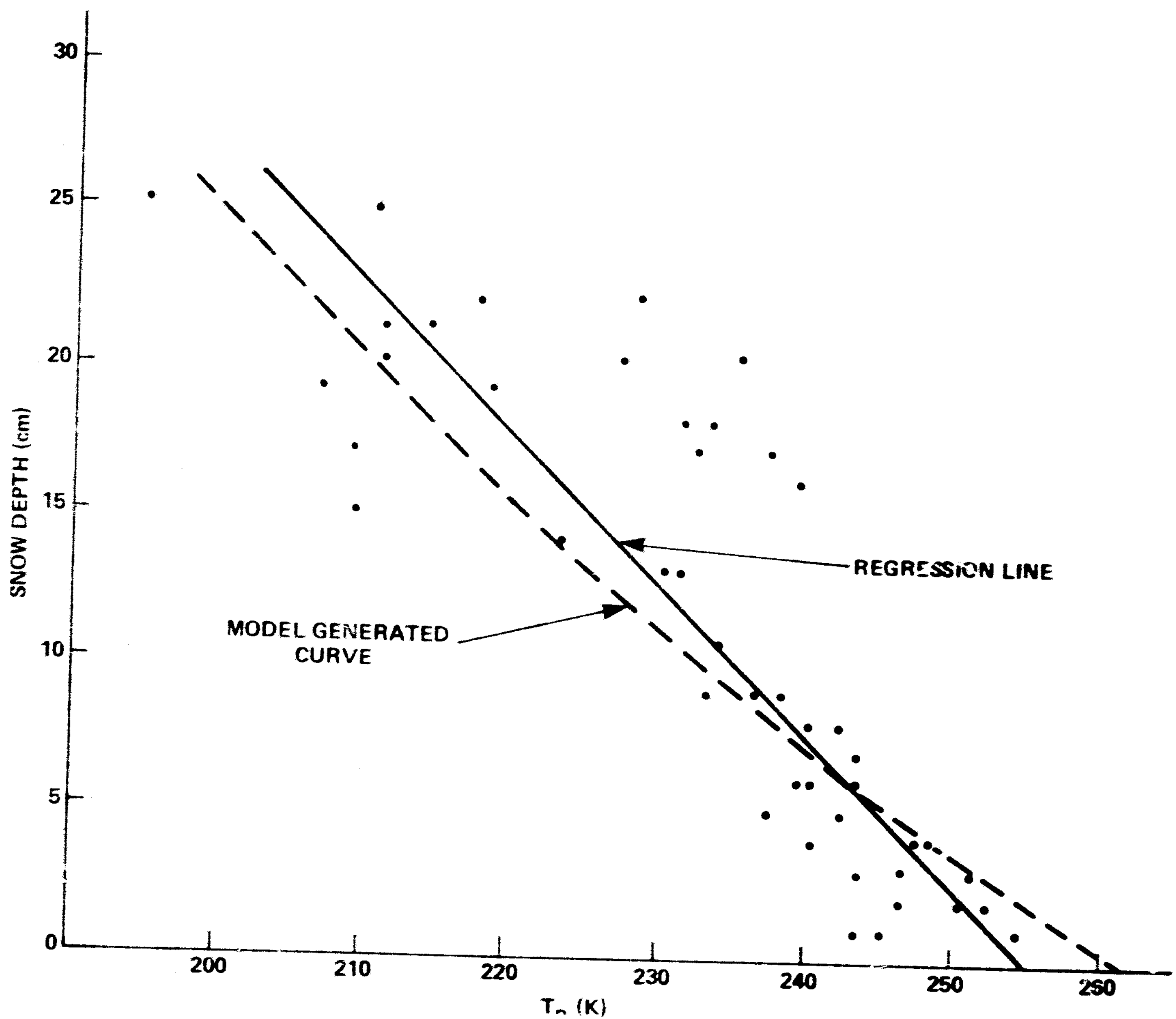
50
100
150
200
250
SNOW DEPTH (cm)


30
25
20
15
10
5
0
SNOW DEPTH (cm)
200
210
220
230
240
250
260
REGRESSION LINE
MODEL GENERATED
CURVE